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INTERPRETATION OF STRAIN MEASUREMENTS ON NUCLEAR PRESSURE VESSELS

Svend Ib Andersen
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Abstract. Selected results from strain measurements on 4 nuclear pressure vessels are presented and discussed.

The measurements were made in several different regions of the vessels: transition zones in vessel heads, flanges and bottom parts, nozzles, internal vessel structure and flange bolts.

The results presented are based on data obtained by approximately 700 strain-gauges, and a comprehensive knowledge of the quality obtained by such measurements is established. It is shown that a thorough control procedure before and after the test as well as a detailed knowledge of the behaviour of the signal from the individual gauges during the test is necessary. If this is omitted, it can be extremely difficult to distinguish between the real structural behaviour and a malfunctioning of a specific gauge installation. In general, most of the measuring results exhibit a very linear behaviour with a negligible zero-shift. However, deviations from linear behaviour are observed

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in several cases. This nonlinearity can be explained by friction (flange connections) or by gaps (concentrical nozzles) in certain regions, whereas local plastic deformations during the first pressure loadings of the vessel seem to be the reason in other regions.

INIS-descriptors: BWR TYPE REACTORS, EXPERIMENTAL DATA, GRAPHS, MECHANICAL TESTS, PERFORMANCE TESTING, PRESSURE VESSELS, PWR TYPE REACTORS, STEELS, STRAIN GAGES, STRAINS, STRESS ANALYSIS, TABLES.

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1. INTRODUCTION

The stress analysis of pressure vessels and vessel components can in most cases be performed relatively economically and reliably for static problems by purely theoretical and numerical analysis. However, experimental stress analysis is still necessary and even required in situations where theoretical analysis is considered inadequate, or for parts where design rules are unavailable [1].

For the designer or the stress analyst, a further advantage turns up when the result from an experimental investigation is available. The result from his computational model can be verified, thus most probably excluding any significant error in this model. This is especially important for complicated components and for large finite-element models, where a considerable amount of input data has to be generated, and where the detailled mesh division is subjected to different restrictions, some of them conflicting with one another.

Only few experimental data from strain measurements on nuclear pressure vessels are published, and they deal mainly with nozzle problems. Van Campen et al [2] published the results from measurements on a nozzle in a 1:4 model vessel and compared them with experimental and theoretical results from a nozzle on a flat plate. Spaas [3] published experimental results for two nozzles in two different PWR-pressure vessels, Tonarelli and Azzola [4] showed results from a BWR-nozzle, and Andersen et al. [5] gave results from a BWR-vessel with internal main circulation pumps. In all this cases, the strain measurements were published in connection with comparisons among different calculational models. Finally, Broekhoven [6] published a few results from a perforated bottom and compared them to photoelastic and steel model results; measurements on flanges and bolts have been published in different connections, for example, recently by Spaas [7] and Joas [8].

The measurements on full-size vessels are in all cases performed during the hydrotest, either in the manufacturer's workshop or at the plant before the initial start-up of the reactor. This means, that the installation technique and procedure is subject to severe restrictions, and there is normally no possibility of repairing the installation and repeat the measurements, a procedure quite normal for investigations performed under laboratary conditions. Due to the long duration between the measurements performed on the individual vessels, the particular skill of the persons involved in the installation and in the measurements is difficult to maintain, and an effective transfer of experience is also hampered.

The present report summarizes the experience obtained by Risø after strain measurements on 4 nuclear pressure vessels in the manufacturer's workshop (Uddcomb Sweden AB) during the hydrotest. The quality of the measurements is discussed, and different types of abnormal behaviour (nonlinearity, zero-shift) are analysed. Selected results from the measurements are presented and the stresses in certain regions, calculated on the basis of the strain measurements, are compared to code requirements.

2. TYPE OF VESSELS

The vessel results presented in this report emanate from strain gauge measurements performed on 3 BWR-vessels and 1 PWR vessel. The 3 BWR-vessels are basically of identical design: the ASEA-ATOM BWR's with internal main circulation pumps. Vessel No. 1, however, has a larger diameter than vessel 2 and 3. Vessel No. 4 is the PWR-vessel, KWU-design.

The vessels are shown schematically in Fig. 1. The BWR-vessels consist of a long cylindrical part connected to the perforated spherical bottom part through a toroidal and conical part. The pump nozzles penetrate the vessel in this toroidal and conical transition zone. The vessel head is spherical and bolted to the vessel by connections to the vessel-head flanges. The internal structure, integral with the vessel, consists of the moderator tank, which is connected to the vessel wall through a pump deck. The large openings in the pump deck is for the pump impeller and stationary blades, and they are thus situated immediately above the pump nozzles.

The PWR-vessel has a spherical bottom and vessel head, and the nozzles are situated in the heavy vessel flange.

All vessels are made of steel, and cladded with stainless steel inside, in most cases with a cladding thickness of 5 mm.

The main dimensions relevant in this connection are given in Table 1, where the theoretical ratio between membrane stresses and pressure is also given.

The BWR-vessels were all pressurized to 111 bar at the hydrotest, whereas the PWR-vessel was pressurized to 227 bar.

3. APPLICATION TECHNIQUE AND QUALITY CONTROL PROCEDURE

The majority of the measuring points had to be placed on the inside surface of the essels and had to work in direct contact with the water used for the pressurizations, at pressures and temperatures up to 230 bar and 50°C.

Though this is one of the more difficult environments for strain-gauges, it was decided to perform the measurements by means of conventional strain-gauge technology, i.e. by adhesive-bonded foil-gauges applied with water protection.

In addition, the mounting of the strain-gauge installations had to be as simple as possible to save time, as the installation of up to several hundred measuring points should be performed in a few days.

Prior to the measurement, an investigation was performed to find the most suitable method of installing strain-gauges. A literature search and application to strain-gauge suppliers yielded no immediately applicable method, and an experimental testing of potentially usable types of adhesives and protections in installations, subjected to simulated environmental conditions, had to be performed [9].

As it is difficult to use clamping fixtures for the bonding and because the limited time for the installation permitted only quick-curing adhesives to be used, the protection should preferably be an easy-to-apply single layer type.

The initial investigations indicated that one combination of adhesive and protection (Hottinger X60/AK 22) was able to perform satisfactorily.

At the following measurements on the reactor vessels 1 and 2, however, some of the measuring points became inoperable due to entrance of water (compare with Table 2).

The laboratory investigation was then expanded in order to find the reason for the failure and perhaps to obtain more reliable methods of installation.

These tests indicated that the material employed hitherto as suitable for the purpose, but that the application procedures hat to follow certain lines. The following measurements were then performed without any significant failures of the gauge installations (see Table 2).

It has been found necessary to employ a series of quality control procedures during the gauge-installation period and on the completed installations before and after the measurements. These tests are essential for both a reliable performance of the gauge installations as well as for an explanation for a possible abnormal behaviour of certain gauges.

The tests involve the following measurements and tests on the gauge installations and measuring system:

- insulation resistance
- deviation from nominal gauge resistance
- "squeeze-test"
- total resistance for the gauge, including leadwires
- shunt test

The measurement of the insulation resistance indicates whether there is a short circuit or moisture in the strain-gauge installation. The insulation resistance will normally by higher than $10^8\Omega$, but will exhibit some temperature dependence [9]. Lower values can be caused by moisture in the installation, caused by water diffusion through the protection, and there exist a risk that the bond between gauge and vessel surface could be affected.

The deviation from the nominal gauge resistance value is always observed when a gauge is bonded, but will normally be moderate (< 1%). Greater values could be caused by damage in the gauge, improper soldering or failure in lead wires.

The "squeeze-test" is performed on the installed gauge, but before the water protection is applied: The strain value is observed when a piece of rubber is pressed against the grid of the gauge, and if the value does not return to the original level after the test, there might be a failure in the bond of that particular gauge, most probably as a void in the bond.

The total resistance of the gauge installation is needed for correction of the measured values; it also gives an indication of possible failures in lead wires, connections and gauge.

The shunt test is performed in order to see if the total measuring link works satisfactorily without any bad connections or switching points. It is performed on each individual channel with a precision resistance, calibrated to give a signal of

1000 or 2000 $\mu\varepsilon$ when a 120 Ω gauge is shunted.

The test procedures are performed at the following stages:

a) After completion of gauge installation, including soldering of lead wires, but before application of moisture protection, the following tests and measurements are made: insulation resistance, deviation from nominal resistance, total gauge resistance and "squeeze-test".
b) During the connection of lead wires to the measuring system and preferably with a water-filled vessel, the insulation resistance, deviation from nominal resistance and total resistance are measured.
c) The shunt test is performed after connection of the measure-ring system, but before the pressure test.
d) After completion of the pressure test, but preferably with water still in the vessel, the same measurements are made as in point b.

4. RESULTS

Provided the insulation resistance for a gauge installation is within the acceptable limits, the relevant measuring channel (wires, electrical contacts, etc.) is without errors and the gauge application procedures have been followed correctly, a linear relationship between the strain-gauge signal and the pressure in the vessel should normally exist.

If there are deviations greater than the expected measuring tolerance from this relationship, a further examination is required in order to seek an explanation.

Nonlinear strain behaviour in a pressure vessel, including a possible zero-shift, can be caused by either nonlinear material behaviour attributed to local yielding, redistribution of residual stresses, or a combination of the effects, or it can be induced by the specific design of the vessel (gaps, friction, etc.).

In order to illustrate this, examples of such strain behaviour is shown in the following. In all of the cases, the gauge installations have performed perfectly, evaluated on the quality control basis mentioned above.

A typical example of material-influenced nonlinearity is shown in Figs. 2-4. The results shown in Figs. 2 and 3 are typical for some strains measured at the internal structure of a BWR-vessel with internal main circulation pumps: the axial strains in the moderator tank skirt in the vicinity of the pump deck are shown in Fig. 2, and the circumferential strains in the pump-impeller opening are shown in Fig. 3. In both cases, a nonlinear strain behaviour as well as a considerable zero shift is observed during the first pressure cycle, whereas the second pressure cycle exhibits a clear linear behaviour with negligible zero shift.

However, the structure has stiffened locally, indicating initial local yielding in the measuring area or in its vicinity. This type of nonlinear material behaviour can be caused either by the design of the vessel (highly loaded local regions) or by not fully relieved residual stresses; these are introduced during the fabrication of this part of the vessel, eventually as a combined effect of them both.

A similar effect is shown in Fig. 4 for measurements in the weld zone at a complicated hill side nozzle. The first pressurization exhibits a nonlinear behaviour, whereas the second is linear and with nearly negligible zero shift.

A settlement of the gauge bond could have caused this type of strain-pressure relationship, decreasing strains with still higher loads, but it is normally not observed with this type of installation, and it should definitely not cause the positive zero shift observed for one of the gauges. It is thus believed that the gauges behave perfectly and that the observed non-linearity and zero shift is caused by local yielding and redistribution of residual stresses in the nozzle region.

Another type of nonlinearity is observed in the concentric cylindrical parts of a pump nozzle. The nozzle is designed with a gap between the internal and external parts, but the two parts can exchange loads via two supporting ring areas. These areas are apparently not in continuous contact with each other, as indicated by the results from the strain gauges in the vicinity of the upper support area. At a pressure higher than the design pressure, the longitudinal bending changes drastically in both cylindrical parts, as shown in Figs. 5, 6 and 7. The results shown are taken from a second pressurization of vessel 1 and 2, and the zero shift is nearly negligible in both cases, indicating that the observed nonlinearity is caused by the specific design. In any case, the measured strains are very small, and an awareness of the phenomenae has importance mainly if analytical results from a linear, elastic calculation has to be compared to the measurements.

The last example of nonlinear behaviour of strain versus pressure is taken from the measurements on the PWR-vessel, vessel No. 4. The radial deformations of the upper and lower flanges are different. At one point of pressure, when the adhesive friction between the flanges is low enough, the flanges will slide against each other. This fact is well known and could be regarded during the first pressurization.

This is clearly illustrated in Fig. 8, where the circumferential strain in the vessel head flange is linear until 150 bar. Above this pressure, the friction in the flange is overcome and causes a jump in the pressure-strain curve. After depressurization the head flange is compressed by the vessel flange, and the subsequent increasing pressurization from 2 to 175 bar did not cause the flanges to slide against each other (Fig. 9). The influence of this sliding/nonsliding of the flanges against each other is pronounced even for the measurements on the nozzle, as seen from Fig. 10. Also the bending in the flange holts is influenced by this phenomenon, as seen in Fig. 11.

5. STRESS LEVELS

The strain measurements have been performed for the pressure load only, and as the number of measuring points for different reasons are limited, it has been possible to distinguish between membrane and bending stresses in only a few cases. It is thus difficult to make a direct comparison between the stresses based on measured values and the ASME-code requirements. The most relevant application of the results is in connection with theoretical predictions or in nozzles, where a stress index is available in the code. In other cases, a comparison has to be made with the membrane stresses in the undisturbed vessel wall, thus anticipating that these stresses meet the code requirements.

For vessel No. 1, measurements were made in the transition zone between the cylindrical vessel part and the spherical bottom both inside and out. The results is shown in Figs. 12 and 13 together with the calculated values from [5]. According to the ASME-terminology, the values represent the primary membrane plus primary bending stresses. The maximal nominal stress is measured in the longitudinal direction and is $\frac{\sigma}{p} = 31$. According to Table 1, the corresponding membrane stress intensity in the cylindrical vessel wall is 21.3. The ratio between the corresponding nominal stress intensities is 1.5. This indicates a well-balanced design according to the ASME-code, which allows 50% higher stress intensity values for membrane plus bending stresses than for membrane stresses alone.

The nozzle results from vessel No. 4 are well-suited to a comparison with the ASME-code stress index design method for nozzles. The highest stresses are observed at the inside corners in a vertical section through the nozzle (see Table 3) where the normalized measured hoop stress at the design pressure is given for positions A and B.

The bending in the flange region leads to slightly greater stresses in point B, and the pressure-induced stresses are largest during the first pressurization. However, in the second pressurization, the flange connection has "settled", and the vessel response is elastic and linear. Averaging the values for positions A and B for this second test gives stress indices which correspond well with the code predictions.

The stresses are classified as peak stresses according to the code, and the allowable ratio between the membrane stresses and membrane-plus-peak stresses is 3. The ratio between the circumferential stress intensity in the vessel wall (Table 1) and the maximum measured stress intensity in the nozzle is 1.66, or well within the code requirements.

Finally, nominal stress intensities in selected areas in the vessels are given in Table 4, whilst the nozzle results for the BWR-vessels are deleted, as these have already been discussed for vessel No. 1 [5]. As the ratio between the design pressure for the PWR-vessel (vessel No. 4) and the BWR-vessel is 2.05, the PWR-values, normalised to the BWR-pressure, are also given in order to facilitate a direct comparison of the stress levels in the two vessel designs. There is no significant difference between the vessels, and the ratio between the stress levels in the cylindrical vessel wall and the regions shown in Table 4 is well within the ASME-code requirements.

6. CONCLUSIONS

Selected results from strain measurements on four nuclear pressure vessels have been presented.

It is shown that reliable results can be achieved with conventional strain gauge technique. A usable bonding and water protection technique is exposed, and it is experienced that careful artisan work and skill in combination with a thorough check procedure is needed for a satisfactory result.

If the results from strain measurements are to be used in connection with a verification of a linear, elastic design calculation, the results from the first pressurization might be irrelevant, as significant nonlinear effects will then be present in several regions. In most cases, these nonlinear effects will have vanished after the first pressurization.

The redistribution of stresses or flange friction effects introduces residual stresses, which locally shifts the level of the mean stresses. This shift might be of the same magnitude as the load-induced stresses, and this eventually would have to be taken into account in the design analysis.

The measured stress levels shown for the four vessels are all well within the ASME-code requirements for pressure loads, which is the only load case that has been dealt with experimentally.

REFERENCES

[1] ASME Boiler and Pressure Vessel Code, Section III, Division 1, Subsections NA and NB. ASME, New York 1977.

[2] van CAMPEN, D.H. et al., The Nozzle-to-Flat-Plate Approach in the Stress Concentration Problem of Nozzle-to-Cylinder Intersection. 1st SMiRT-Conference, paper G 2/4, Berlin 1971.

[3] SPAAS, H.A.C.M., Determination of Stress Concentrations at Nozzle-to-Cylinder Intersections and Comparison with Experimental Analysis. 2nd Int. Conf. on Pressure Vessel Technology, paper I-11, San Antonio, 1973.

[4] TONARELLI, L.C., AZZOLA, M.D., Axisymmetrical Model for Nozzle on Cylindrical Shell and Comparison with Experimental Results. 4th SMiRT-Conference, paper G 8/3, San Francisco 1977.

[5] ANDERSEN, S.I. et al., Stress Analysis of a MCP Pressure Vessel Nozzle. 4th SMiRT-Conference, paper G 8/4, San Francisco 1977.

[6] BROEKHOVEN, M.J.G., Experimental and Theoretical Stress Analysis of Perforated Bottom Models of the Dodewaard Reactor Vessel. 1st Int. Conference on Pressure Vessel Technology, Paper I-27, Delft 1969.

[7] SPAAS, H.A.C.M., Deformation Behaviour of Large, High-Pressure Vessel Flanges. Chapter 1. In: Nichols, R.W. (ed.): Developments in Stress Analysis for Pressurized Components. Appl. Science Publishers, 1977, p. 1-47.

[8] Joas, H., Hochtemperaturdehnungsmessungen an den Stiftsschrauben von Kernreaktordruckbehältern. 6th Int. Conf. on Experimental Stress Analysis, München 1978, VDI-Berichte nr. 313, p. 879-885.

[9] Engbæk, P. et al, Performance of Strain Gauge Installations in Pressurized Water at Elevated Temperatures. 6th Int. Conf. on Experimental Stress Analysis, München 1978, VDI-Berichte nr. 313, p. 565-571.

Table No. 1. Vessel Dimensions.

Vessel No.	Pressure p [MPa]		Internal diameter D_i [m]	Wall thickness t mm			Membrane stresses in cylindrical vessel wall, normalized with the pressure, σ_h/p	Flange Bolts		
	Design	Proof test		cyl. part	bottom	head		no.	Stem diam [mm]	$\frac{\sigma_b}{p}$
1	8.5	11.1	6.4	154	180 (165)		21.3	64	145	30.4
2	8.5	11.1	5.54	~150	180 (160)		19.0	60	130	30.3
3	8.5	11.1	5.54	~150	180 (160)		19.0	60	130	30.3
4	17.5	22.7	5.0	250	250	242	10.5 (5.01 in flange)	52	190/30	12.0

Note: The normalized membrane stress $\frac{\sigma_h}{p}$ is calculated as:

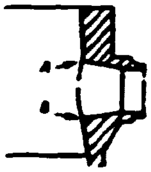
$$\frac{\sigma_h}{p} = \frac{(D_i+t)}{2t}$$

Table no. 2. Number of Strain Measuring Positions

Vessel No.	Total number of strain gauges	Number of gauges inside the vessel (under pressure)	Number on flange bolts	Number of gauges which failed	
				in all	inside vessel (under pressure)
1	306	216	51	83	53
2	203	130	30	73	69
3	68	48	20	0	0
4	87	39	12	1	1
5	78	39	-	0	0
total	742	472		157	123

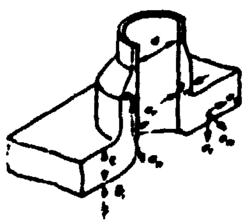
Note: Vessel No. 5 is a nonnuclear vessel, where strain-measurements were performed using the same technique as for the nuclear vessels.

Table No. 3. Normalized stresses $\sigma n/p$ in hoop direction and stress indices for nozzle, vessel no. 4.

	1. pressurization			2. pressurization		
	$\frac{\sigma_n}{p}$	K_n	K_1	$\frac{\sigma_n}{p}$	K_n	K_1
Position A	17.54	3.50	3.70	14.57	2.91	3.11
Position B	18.11	3.61	3.81	16.23	3.24	3.44
Average of A and B	17.83	3.56	3.66	15.40	3.07	3.27

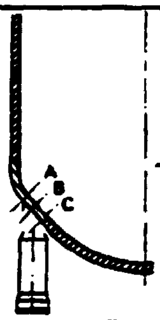
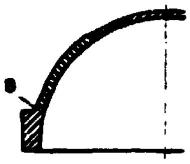
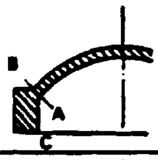
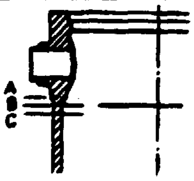
Note: ASME III, table NB 3338.2(c)-1: $K_n = 3.1$, $K_1 = 3.3$

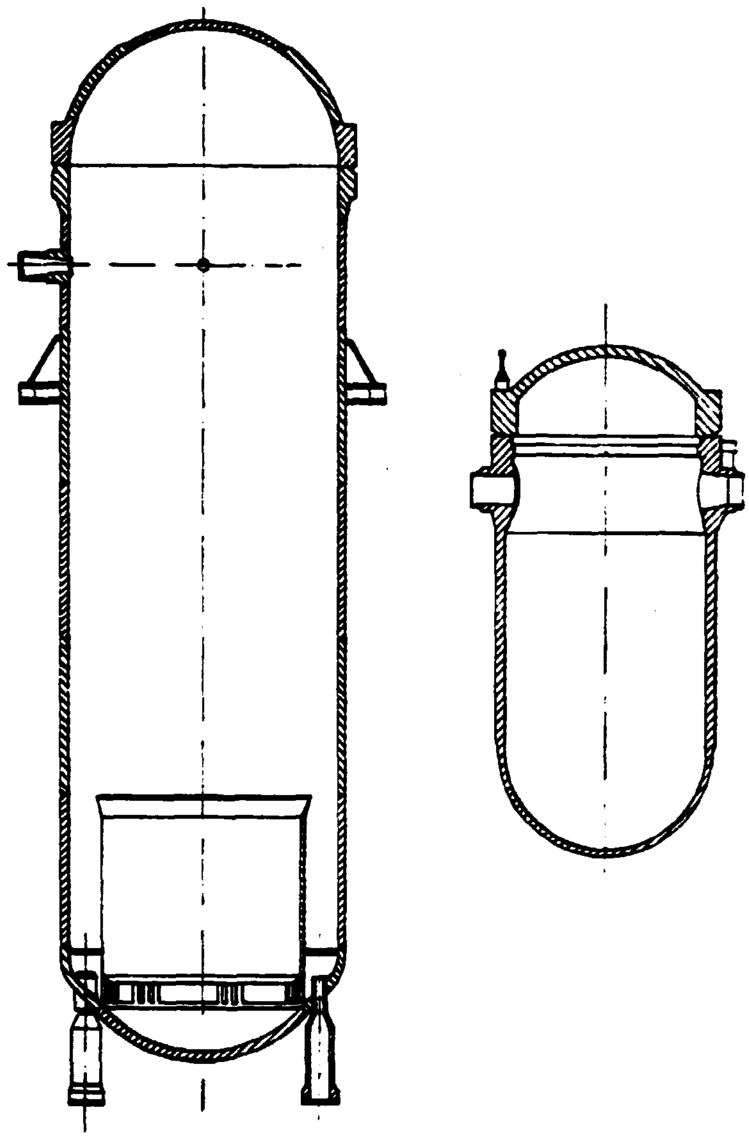
$K_n = \frac{\sigma_n}{\sigma_h}$, $K_1 = \frac{S}{\sigma_h}$, where S is the stress intensity (combined stress)



$$\left.\begin{array}{l} D_i/t = 9.0 \\ d/D_i = 0.16 \end{array}\right\} \text{vessel No.4}$$

Table No. 4. Stress intensities in various regions, normalized with the pressure.

	Vessel No.	Type of stresses	Stress intensity normalized with pressure, S/P A	B	C	Theoretical cylindrical vessel wall stress σ_h/p
	1	membrane	8.53	8.59	10.06	21
		membrane plus bending	24.76	9.47	17.47	
	2	membrane	9.41	7.65	8.53	~ 19
		membrane plus bending	20.76	10.24	12.88	
	1	membrane plus bending		11.9		21
	4	membrane plus bending	15.57 (32.1)	2.66 (5.5)	9.51 (19.6)	10.5 (21.6)
	4	membrane	9.80 (20.2)	9.57 (19.7)	10.57 (21.8)	
		membrane plus bending	11.0 (22.6)	10.94 (22.5)	11.60 (23.9)	



a. b.

Fig. 1: Configuration of investigated pressure vessels.
a: BWR-vessels b: PWR-vessel.

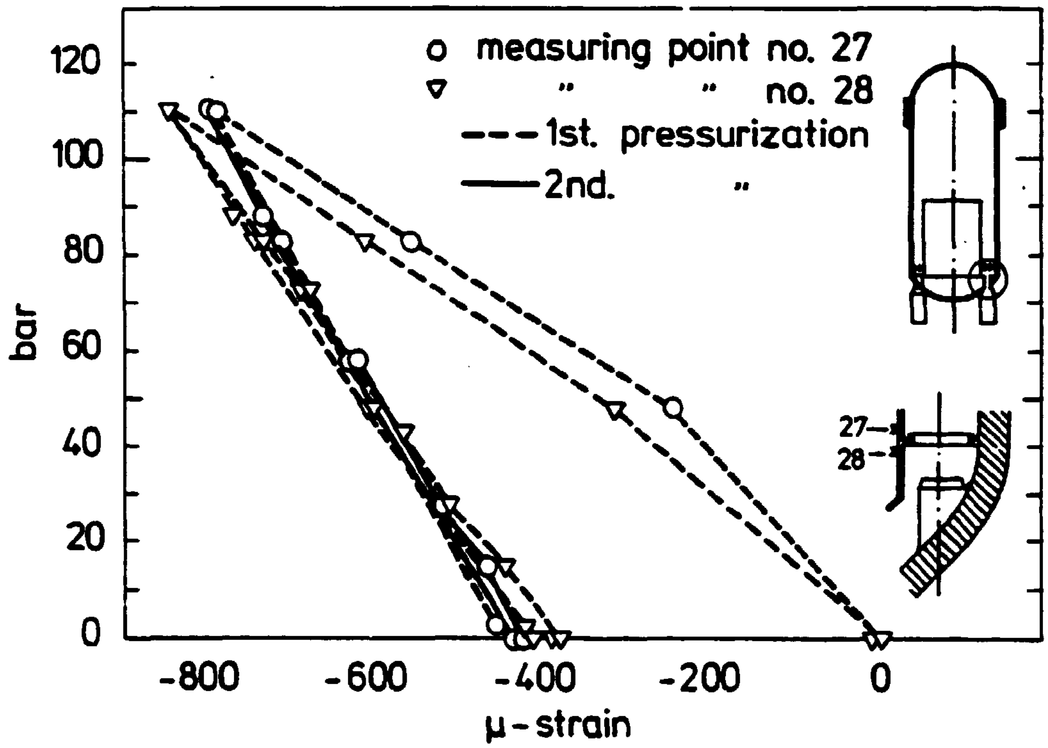


Fig. 2: Strain values measured at the internal vessel structure vessel No. 2.

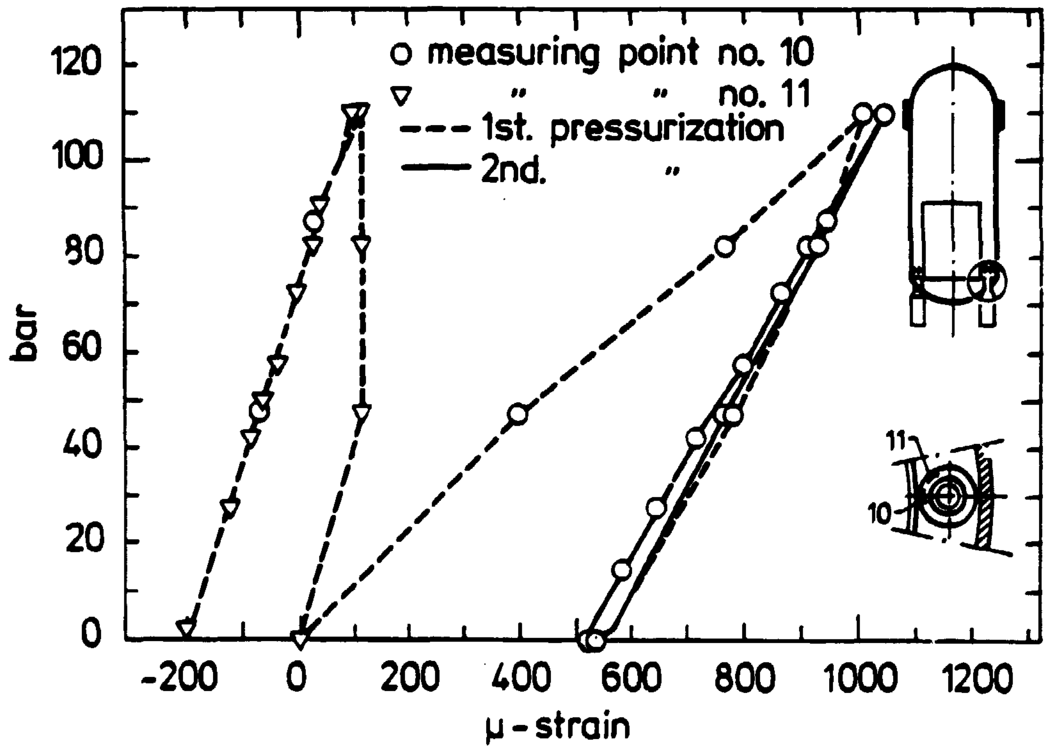


Fig. 3: Circumferential strains in pump openings, vessel No. 2.

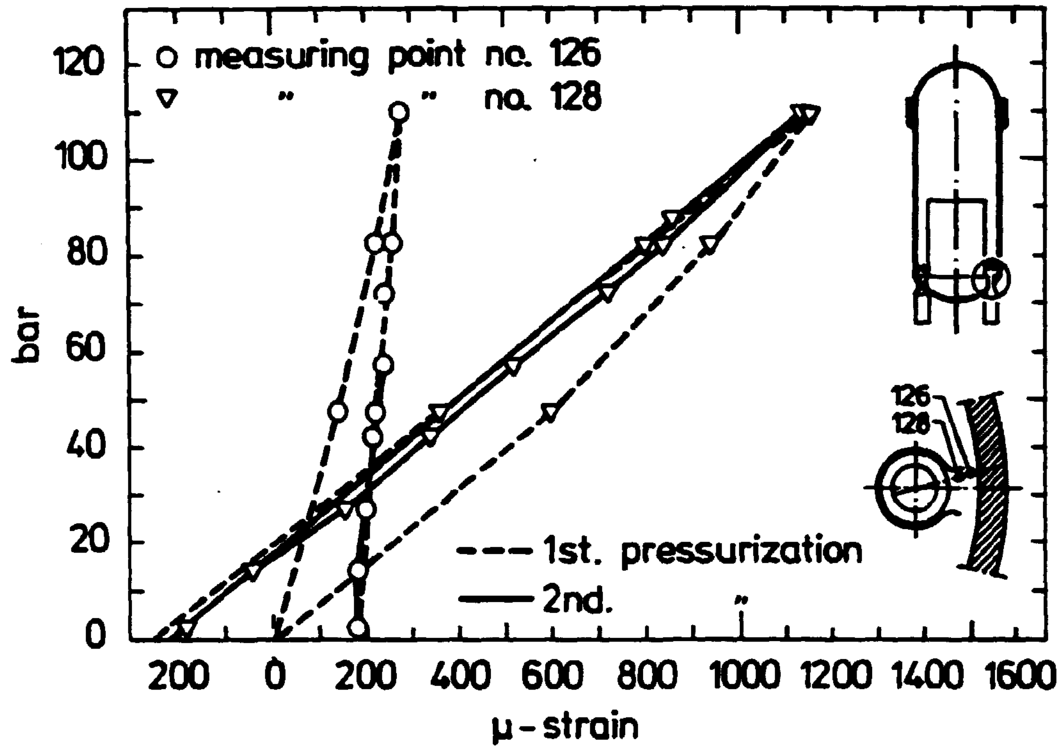


Fig. 4: Typical strain values for pump nozzle, vessel No. 2.

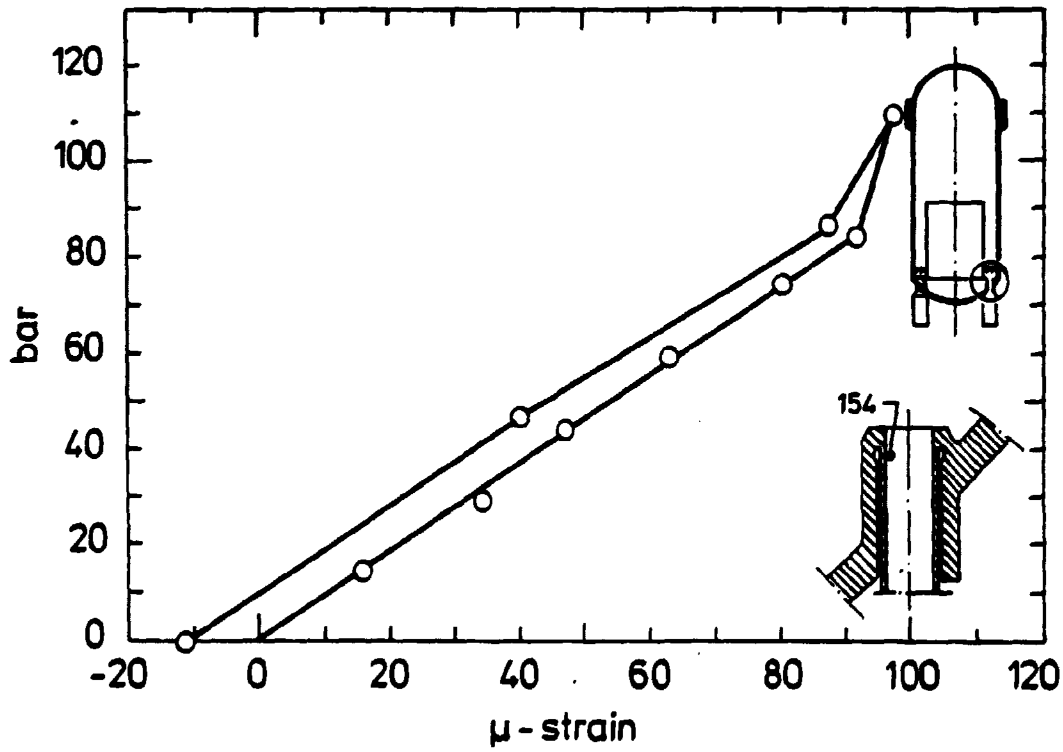


Fig. 5: Axial strains in internal pump nozzle part, vessel No. 2.

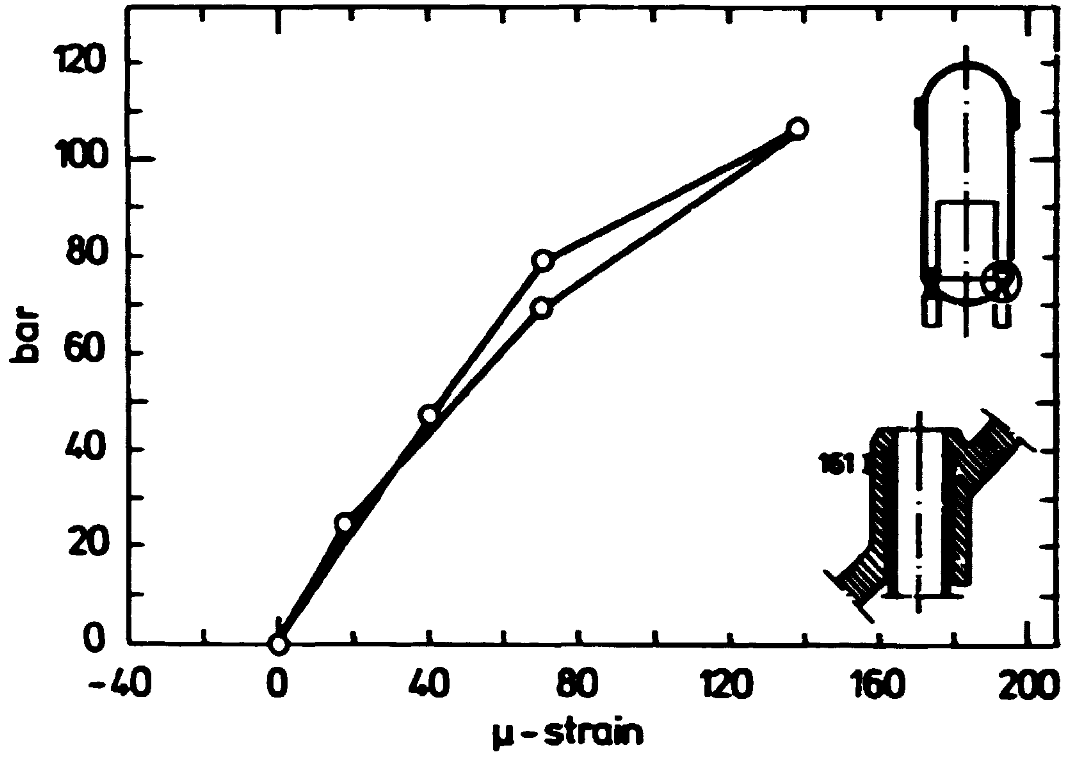


Fig. 6: Axial strain at external pump nozzle part, vessel No. 1.

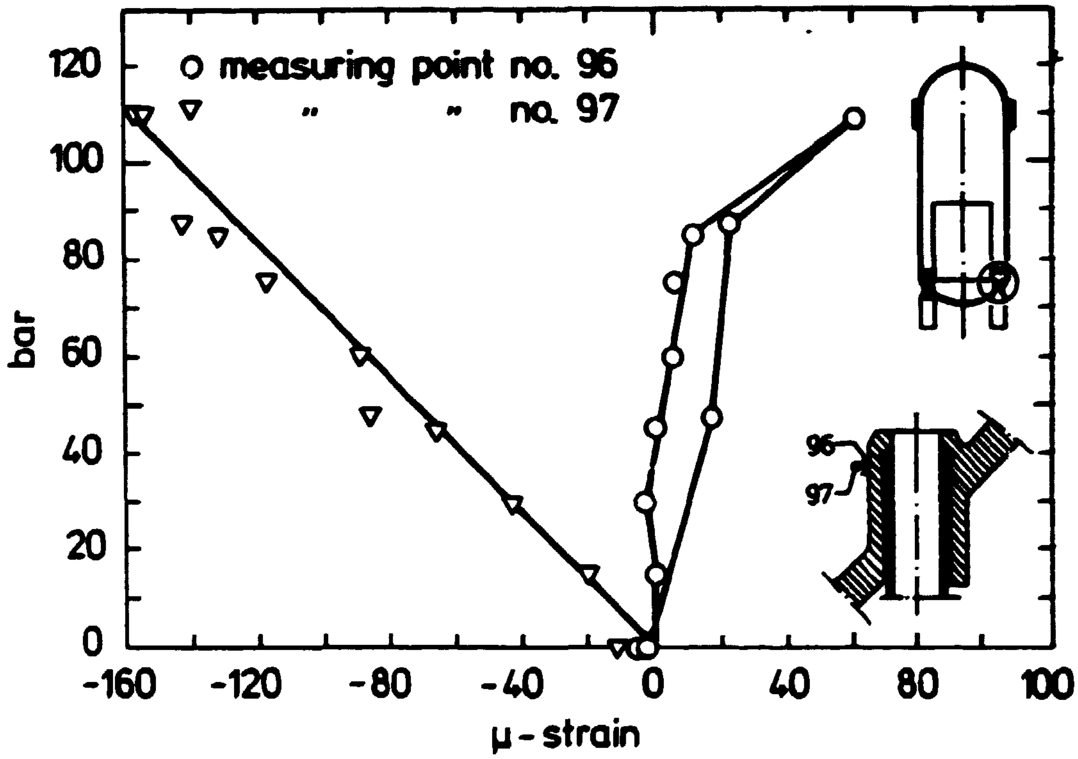


Fig. 7: Circumferential and axial strains at external pump nozzle part, vessel No. 2.

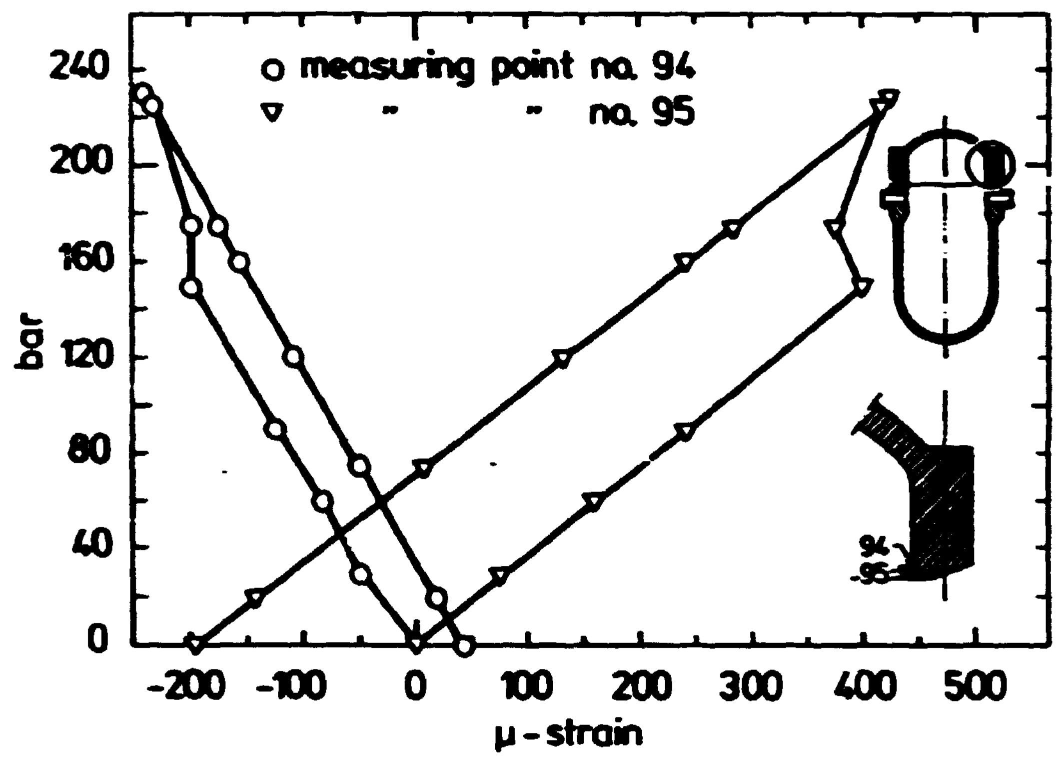


Fig. 8: Strains measured at vessel head flange, vessel No. 4 1st pressurization.

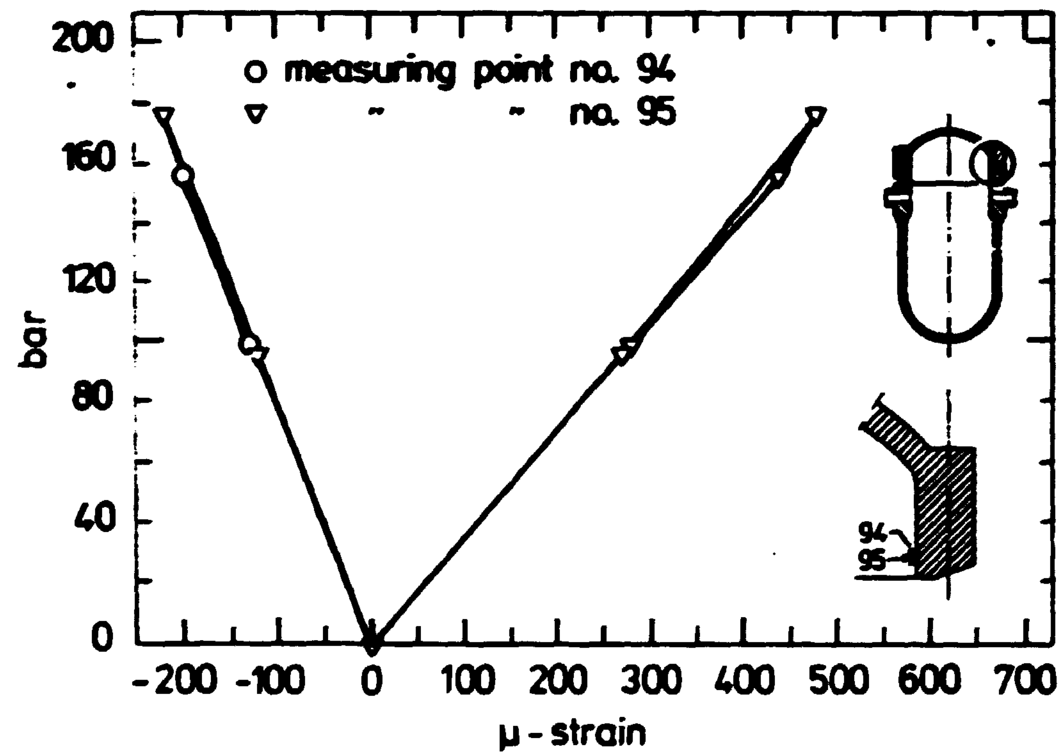


Fig. 9: Same as Fig. 8, but for 2nd pressurization.

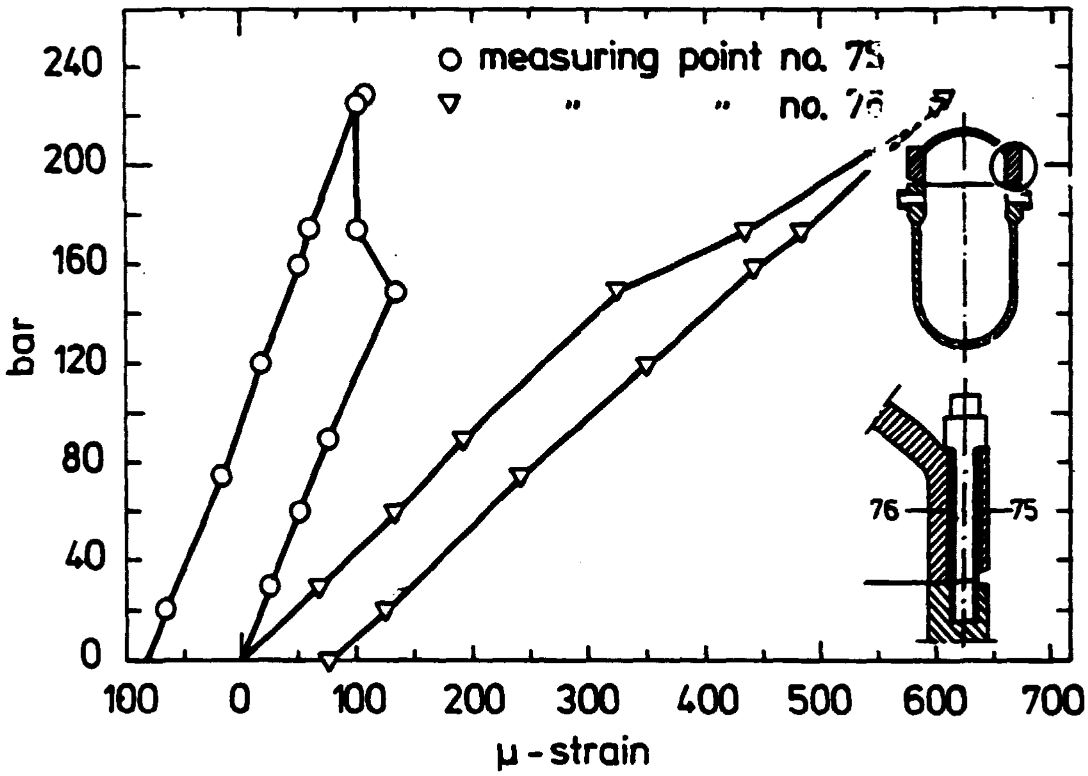


Fig. 10: Axial strains in flange bolts during 1st pressurization, vessel No. 4.

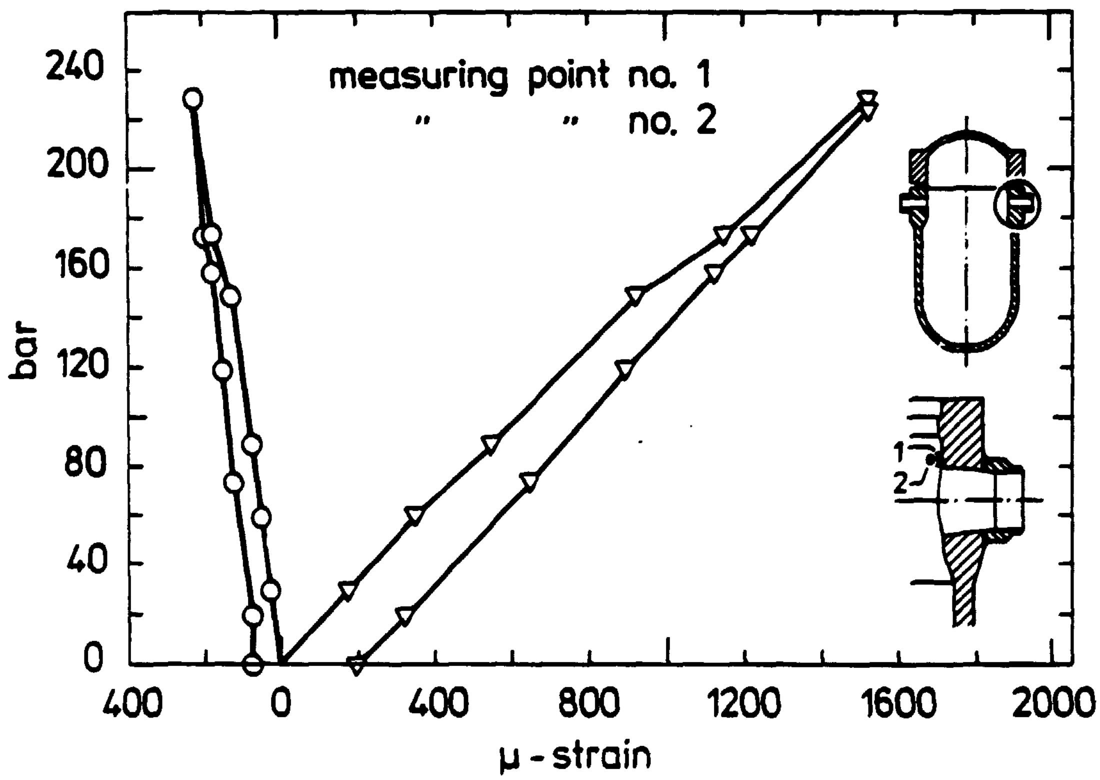


Fig. 11: Strains measured at internal nozzle corner during 1st pressurization, nozzle, No. 4.

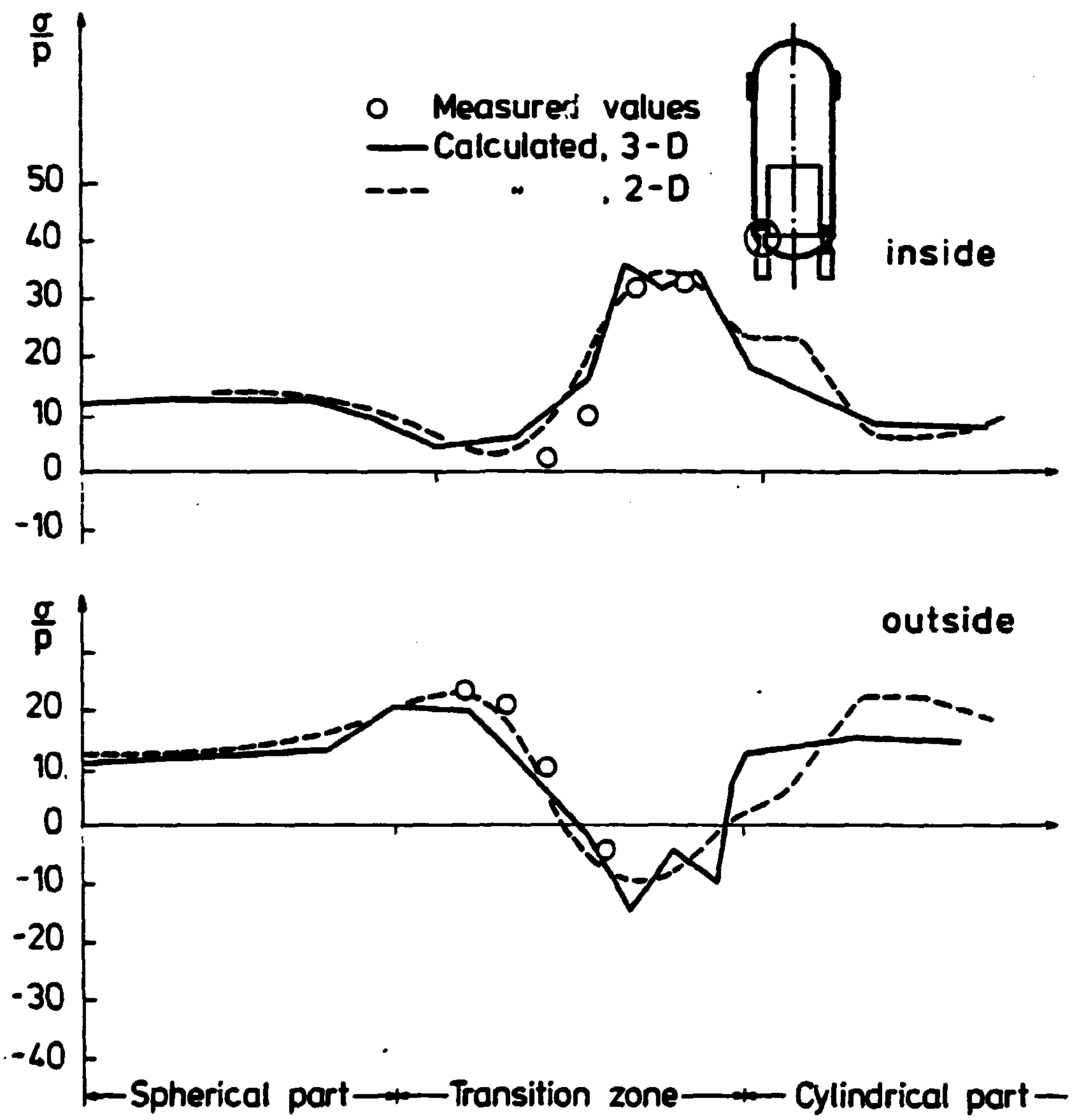


Fig. 12: Longitudinal stresses in vessel wall. Measured values values compared to 2- and 3-D ca culations. Vessel No. 1.

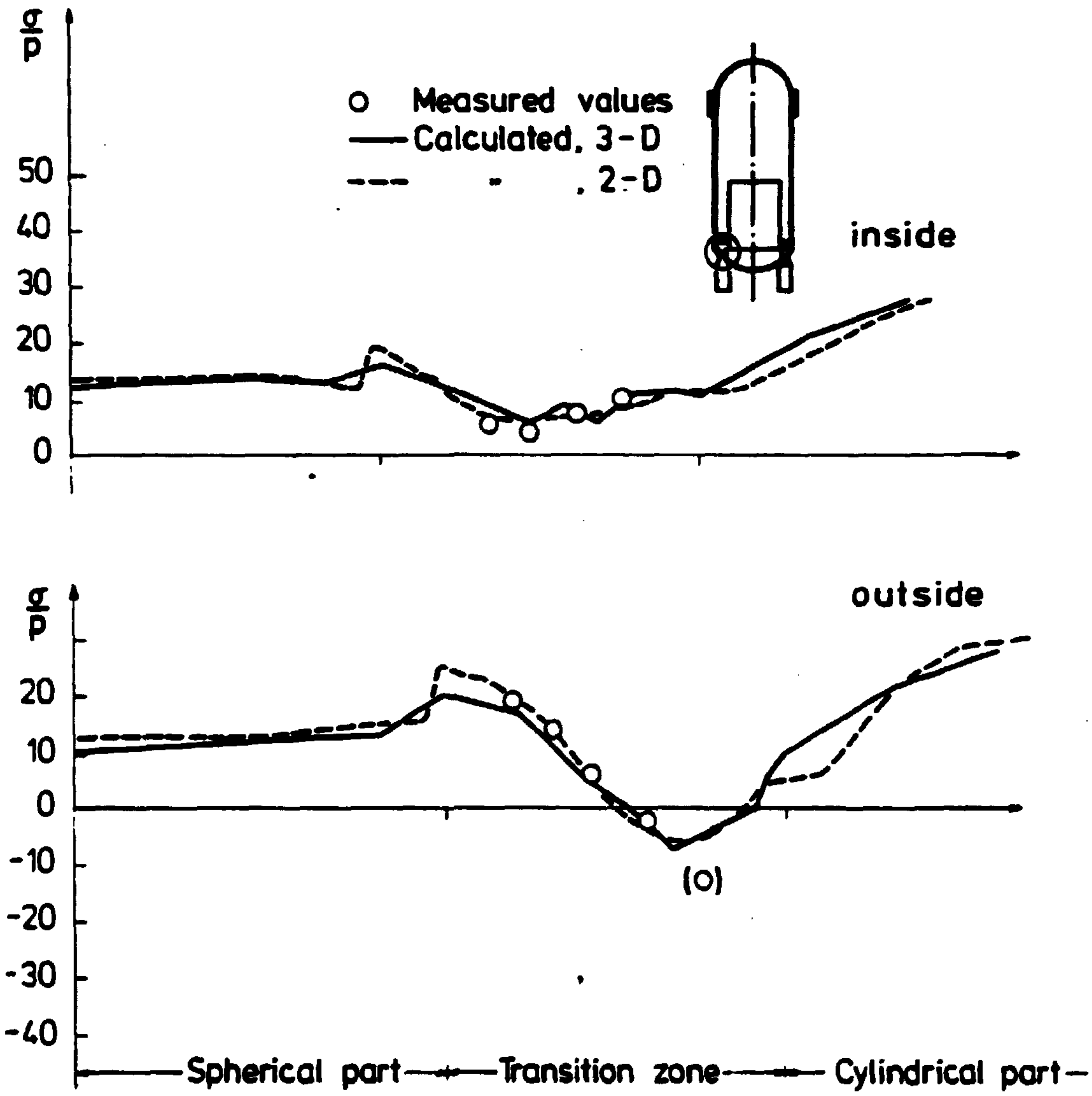


Fig. 13: Circumferential stresses at the same positions as Fig. 12.

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Abstract

Selected results from strain measurements on 4 nuclear pressure vessels are presented and discussed.

The measurements were made in several different regions of the vessels: transition zones in vessel heads, flanges and bottom parts, nozzles, internal vessel structure and flange bolts.

The results presented are based on data obtained by approximately 700 strain-gauges, and a comprehensive knowledge of the quality obtained by such measurements are established. It is shown, that a thorough control procedure before and after the test as well as a detailed knowledge of the behaviour of the signal from the individual gauges during the test is necessary. If this is omitted, it can be extremely difficult to distinguish between the real structural behaviour and a malfunctioning of a specific gauge installation. In general, most of the measuring results exhibits a nice linear behaviour with a negligible zero-shift. However, deviations from linear behaviour are observed in several cases. This nonlinearity can be explained by friction (flange connections) or by gaps (concentrical nozzles) in certain regions, whereas local plastic deformations during the first pressure loadings of the vessel seem to be the reason in other regions.

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